PERFORMANCE-BASED FIRE PROTECTION OF HISTORICAL STRUCTURES

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Performance-based Regulatory Systems (PBRS) are being implemented in many countries, replacing the traditional prescriptive systems. These PBRS are especially attractive for addressing in a rational way the special needs of unique buildings, and there are no more unique buildings than those of historical or cultural significance. Thus, performance approaches are well suited to finding the balance between the need to protect often-irreplaceable buildings and their contents and the desire to preserve the significant historical or cultural aspects of the building.

In this paper the authors will discuss some important considerations in using performance approaches in the development of a fire protection strategy for historical structures and will cite examples of how this was done in a recent restoration design of a historic theater in Bari, Italy.

Performance vs. Prescriptive

Bidding regulations in any country reflect the public expectation for the built environment with regard to the minimum acceptable requirements for health, safety, and welfare, and in some cases for environmental, energy, and culture. Historically, building regulations have been prescriptive in form, describing the acceptability of, or requirements for materials, products and systems that have been shown by experience to result in acceptable buildings. Such prescriptive systems have served well as evidenced by the fact that failures rarely occur in even minimally code compliant buildings.

A major shortcoming of prescriptive systems is that they do not work well in unique buildings or where the possible solutions are in some way constrained. Frequently encountered constraints include aesthetic objections to the degree of compartmentation required in the regulations or an inability to meet egress requirements such as the required number of exits or maximum travel distances, due to building size or site restrictions. When these situations occur, designers usually use the equivalency provisions included in most prescriptive regulations that state[1],

> *"An alternative material, design, or method of construction shall be approved where the building official finds that the proposed design is satisfactory und complies with the intent of the provisions of this code and that the material .. is for the purpose intended at least the equivalent of that prescribed..."*

But the trick here is reaching consensus on the intent of the code and on what is equivalent to that prescribed. While there are some systems that attempt to quantify equivalency, such as the Fire Safety Evaluation Systems (FSES) published in NFPA 101A[2], such systems must be constructed for specific occupancy types and must be continually recalibrated as the prescriptive requirements evolve.

It is these points that make the performance approach attractive, especially for the unique or highly constrained building – and historical structures are usually both. Performance-based regulations are about required outcomes rather than about specific solutions and explicitly describe the intent of the code, unambiguously. Further, the process described in such documents as the *SFPE Engineering Guide to Performance-based Fire Protection. Analysis and Design of Buildings*[3] is built around a consensus of stakeholders, including the designers, owners, builders, and regulatory officials, as to the objectives and the suitability of the methods proposed to achieve those objectives.

Objectives of Historical Preservation

The protection of historical structures is unlike that of almost any other type of building. In some cases the objective is to preserve the structure itself, sometimes it is the contents that is of most concern, and sometimes it is both. In some cases the aesthetics or the interior and exterior architectural details are significant and sometimes the internal details of the structure itself are unique and in need of preservation as part of the historical record. Thus, the art of historical preservation must be free to find solutions that are consistent with the particular needs of the building. Such freedom simply cannot be achieved with prescriptive approaches developed with the typical building in mind.

These ideas underlie NFPA's *Code fur Fire Protection of Historic Structures* (NFPA 914). This Code[4], "... describes fire safety requirements for the protection of historic structures and for those who operate, use, or visit them. It covers ongoing operations. renovation, and restoration and acknowledges the need to preserve historic character." It includes explicit goals and objectives for life safety and historic preservation (see section 1.4 of NFPA 914) that are applicable to either prescriptive or performance solutions. For performance approaches there are eight design fire scenarios specified that are identical to those included in the Performance-based Design Option of the *Life Safety Code* (NFPA 101)[5]. The protection of museum and library collections is the subject of another document, NFPA 909, *Code for the Prutection of Cultural Resources*[6].

The process discussed in NFPA 914 begins with a detailed survey to document historic elements, spaces and features, both interior and exterior, and to prioritize their historical or cultural significance should some compromise be necessary to reach minimum safety objectives. Then the fire hazards and safety deficiencies are identified and compliance options are determined that satisfy safety objectives without sacrificing historical features. Solutions can be selected from traditional, prescriptive solutions, risk indexing, or perforinance analysis approaches, based on which meet the safety objectives with the least impact on historical features. Care is urged that all parties involved in the construction, including the workers, understand the significant features that are to be preserved, and periodic audits of the work is required.

Unique Issues of Historical Preservation

Preserving the history of a building can involve some unique and sometimes contradictory issues. The older the building, the more likely that it had been at least partially destroyed and repaired. These repairs then become an integral part of the history of the building. In the UK, many castles built in the middle ages were destroyed by fire or explosives during the English Civil War (1642-1648) to prevent their use by one side or the other. Similarly, many Abbeys were burned to the ground when the Henry VIII broke away from the Roman Catholic Church and founded the Church of England (*ca* 1538). Any attempt to restore these buildings would destroy this part of their history.

Dating from the 11th century, the Stave churches of Norway are important because they represent the beginnings of wooden, post and beam construction. Built entirely of wood those that still exist have been extensively repaired but retain the structural elements essential to their historical significance. Larger structures that provide examples of structural design that do not meet modern structural safety requirements are especially difficult to retrofit to modern code while retaining their historical value.

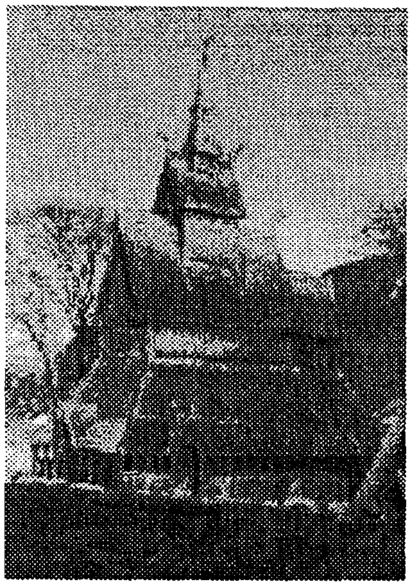

Figure 1- Hopperstad church **in Vik,** Norway was **built** around 1200AD

Fire has long been an enemy of historical structures, with some older structures falling victim many times. One example is the LaFenice Theatre (Venice Opera House) that first opened in 1792 on the site of a theater that burned down in 1773. The construction took two years because the building suffered a fire during construction and had to be rebuilt. It was again extensively damaged by fire in 1836, and is currently being rebuilt after again being totally gutted by fire in 1996. In prior reconstructions, materials and techniques reflected the norms of the time because historical preservation is a modern concept. Today, we want to preserve the past but these old buildings generally exhibit combustible construction and inadequate exits-- long, single paths of travel, narrow stairways and unprotected vertical openings that violate modern Codes and fire protection practices.

Fire Precautions During Construction, Repair, and Renovation

The NFPA 914 Code highlights the need for special care during work projects when the structure is particularly vulnerable. At this time there are temporary collections of combustibles and construction equipment as well as operations that can represent sources of ignition not normally present. Ceilings and walls may be open for repair, exposing combustible structural elements and void spaces that might allow a fire to spread throughout the structure. Existing fire protection equipment may be disabled or removed as a part of the work. Many disastrous fires in historical structures have occurred during renovation activities, such as the 1992 Windsor Castle fire7 and the Venice Opera House fire[8].

Prevention and Special Events

The prevention of threats is crucial in historical structures because any fire will cause some damage to structure or contents. Many historical structures are at least occasionally the scene of scientific studies that may involve access to non-public areas and the conduct of some laboratory activities that each must be evaluated for safety and security.

Historical structures are also frequently the scene of special events that may bring large occupant loads, consumption of alcohol that may impair these occupants, and catering or special food preparation activities that can involve additional quantities of combustibles and ignition sources. All activities at special events need to be evaluated and precautions taken to avoid threats. Large events should involve the local fire brigades who may wish to employ a process of formal review, inspection, and permitting for potentially hazardous operations.

Renovation of a Historic Theater in Italy

One of the main problems with regard to the historical theaters in Italy over the last decade has been their compliance with the new fire protection regulations that were defined at the end of 1980s. Where the decision was made to strictly coinply with the regulations the result has all too often been the complete destruction of the historical value of these buildings. They retain what could be called an "historical appearance" but, underneath, there are concrete slabs in place of timber floors (for instance the Teatro Verdi in Salerno), fiberglass decorations instead of wood and gypsum ones (the Teatro Comunale in Benevento), intumescent varnishes used on various surfaces such as wood partitions and structural elements, and even on wallpaper (for instance the Teatro Verdi in Busseto)

Fortunately, this has occurred for oiily a limited number of historical theaters while the remaining ones, essentially the most famous, went through a quite difficult period. Authorities threatened the suspension of public activities for safety reasons, and some suggested the institution of guards and surveillance to protect against fire.

The "Teatro comunale PICCINNI" in Ban

In this scenario the fire protection and rehabilitation design of the "Teatro comunale Niccolò Piccinni" in Bari (in the south of Italy) can be considered one of the first examples in Italy, of a design intended to meet all objectives from both fire safety and functional points of view, while preserving the historical character.

It was designed following the so-called "alternate approaches," a means explicitly provided for those cases in which it is not possible to explicitly comply with the fire protection regulations, Here, additional features had to be employed to assure a safety level equivalent to what could be achieved if the regulations were prescriptively followed.

The intent of the design team was to emphasize the performance-based approach. This was done mainly with respect to the fire resistance of structural elements and smoke propagation. Only a few of the approaches identified could be used in the design due to restrictions still present in the regulations (that do not yet include performance-based techniques) and the compulsory elements that had to be included. In the end however, the solutions employed resulted in a final design consistent with the building's character and satisfying functionality and safety needs.

Built in the second half of 19^{th} century' (it **was** opened to the public on October 4, 1854), the Teatro Piccinni endured to today, unmodified. In 1913, a renovation involving decorative features and using the Royal Theater in Naples as a model. Antonio Niccolini, the same architect who performed the Piccinni design, this theater's reconstruction after an 1837 fire. But the structural elements of the main hall remained untouched, in spite of various projects in following years ranging from accommodating a larger audience to the complete rebuilding of the interior. This was mainly due to the construction at the beginning of 20^{th} century of a new and much bigger Theater": the Teatro Petruzzelli having a capacity of more than 3000 people.

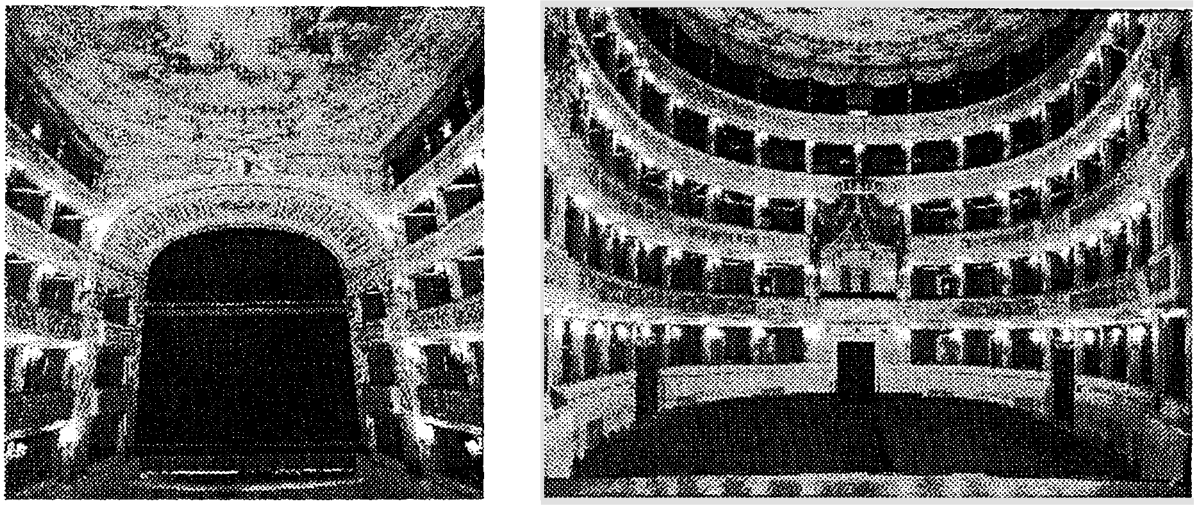

Figure 2- Interior **views** of the PICCINNI Theater

The theater forms the central part of a bigger building whose East and West wings constitute the Town Hall. The town hall was completed during the second half of 19th century and is characterized by walls constructed of local stone and vaulted rooms. The theater with the exception of the front including the main entrance and the foyer (all vaulted parts), is a mix of stone and wood:

- stone walls and wooden floors for all spaces around and close to the main hall (i.e.: corridors);
- wooden floors supported by stone walls (on the exterior side) and wooden poles (an the interior side) for the main hall (comprising parterre, 4 rows of boxes and the gallery).

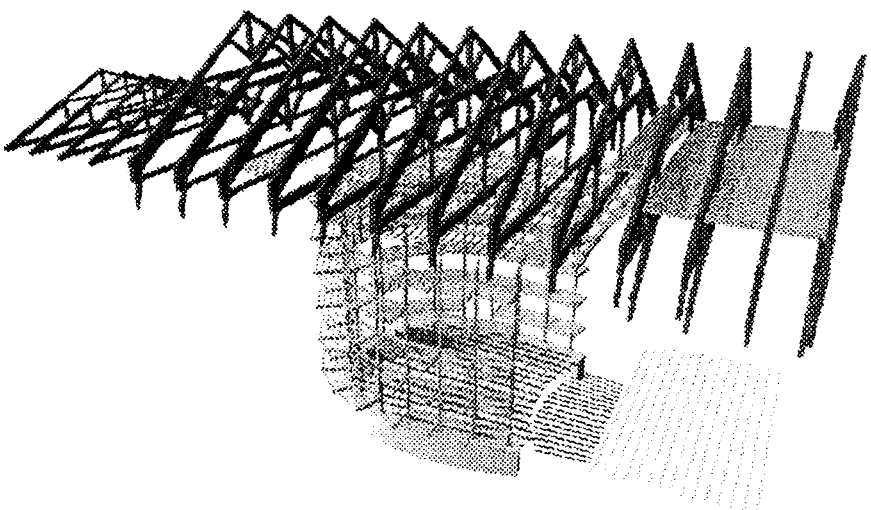

Figure 3 – Presence of **wooden** structures in the PICCINNI theater

In addition, the roof of the main hall and the stage are wood with composite "palladiane" trusses covering a span of more than 20 meters. In 1913, steel-framed floors were installed to replace the corridor planks that were crumbling. **As** a result inside the horseshoe shaped wall defining the main hall, all materials, either structural or decorative, are combustible: wooden slabs, wooden partitions between boxes (partially fabric covered), wooden and papier-mâché decorations. canvas painted ceiling on wooden slab, roof structures, velvet covered wooden balconies, armchairs. curtains and so on. Most wooden parts in the "sala" (i.e., the main hall) are decorated with elements such as gilt frames or grooves.

In addition to the combustible materials, another fire safety deficiency identified was deficient egress capacity for the number of patrons. In particular, the gallery was served by only one egress staircase shared with the municipal office part of the building.

Preliminary building analysis

Before formulating any design approach the theater was studied in detail in all its parts: structural, decorative and functional. Walls were studied by means of non-destructive techniques: endoscopy, flat jack compression tests, acoustic tests and so on. Condition and prior finishes of wood were studied by examination of samples collected that were later used to determine load carrying capacity. Finite element models were developed to examine structural behaviour of different parts including roof trusses. Original colors and finishings were identified by means of microscopic analysis. Consequently, appropriate restoration techniques were defined for all the decorative features.

With regard to functionality, it was identified that, besides machinery used for manipulating scenery on stage, there was a general lack of space for supporting activities. This was mainly due to these spaces having been converted over time to different uses (town hall necessities).
This was addressed by annexing to the theater selected parts of the reinaining building (mainly for a new staircase and for the new artists' dressing rooms) and by re-designating spaces belonging to the theater. Among these is the great room in the attic once used by scene-designers now designed as the theater's museum and conference hall.

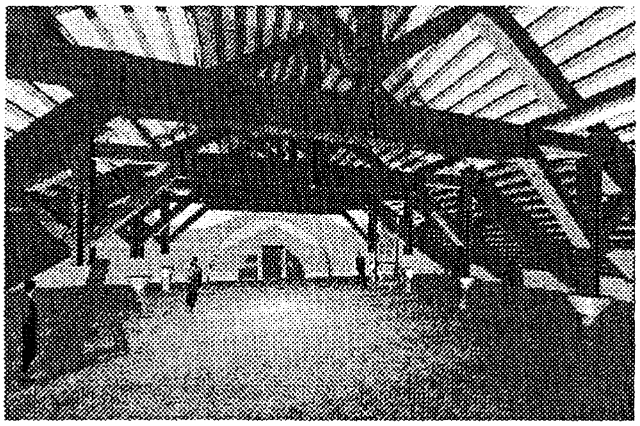

Figure 4 – The attic as Theater's museum and conference hall

Fire compartments definition

One of the first measures considered was to reduce the total fire load by dividing the theater into different compartments. Because a main part of the fire load is the roof structures, the "sala" was considered separated from the roof by mean of a special "zone" [not really a compartment) represented by the space between the ceiling of the "sala" (painted canvas on wooden slab) and the attic floor (a wooden slab supported by the trusses' wooden tie beams).

This zone, referred to as "plafond", was considered as a separating element between the "sala" and the attic that had to be rendered adequately fire resistant. No building equipment or services penetrated this zone except for smoke detectors and a gas (PF23) automatic fire-extinguishing system. To assure adequate fire resistance of the separation between the "sala" and the plafond a fire resistant light ceiling (a “membrane ceiling”) provided an appropriate separation from the parterre ceiling (so as not to affect its acoustic characteristics) hung from the wooden tie beams. For the same reason, the attic floor was determined to be capable of resisting the roof fire load. By these means the theater was subdivided in two compartments: parterre, boxes and gallery (the main hall - comp.2) and the roof (the theater’s museum and conference hall - comp.3). The third compartment is the stage (comp. 1), separated from the main hall by a fire resistant (presidium) curtain.

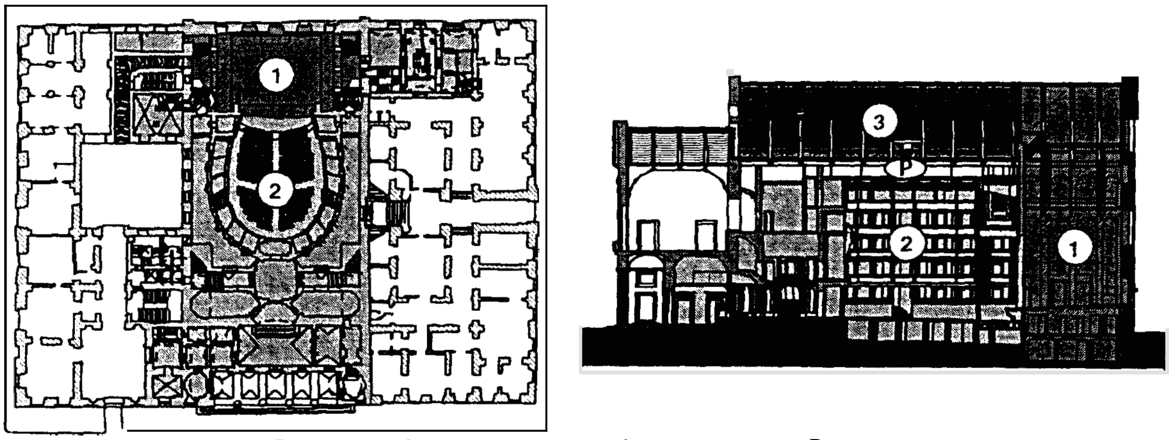

Figure 5 – Theater’s plan and section – 1,2,3: fire compartments – P: plafond zone

Provision of new escape routes

Three staircases were added to provide escape routes sufficient for the total audience capacity. Two of them, specially shaped to reduce overall dimensions, were located at both ends of the corridor serving the boxes. Their symmetrical positioning allows for efficient exit flow. The third new staircase was located at the east side of the theater utilizing part of the adjacent building, facing an interior open atrium. These locations were the only ones possible because the theater was practically surrounded by the town hall building and because these solutions conflicted less with structural and functional constraints. These new staircases were extended to the new conference room and museum space in the attic to serve as escape routes for this level whose occupancy was about 300 people, though approved as not being occupied at the same time as the theater.

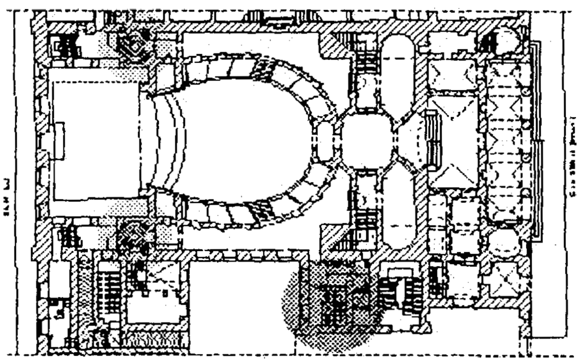

Figure *6* - Position of the new staircases

Fire detection systems

The theater and the new spaces in the attic were equipped with a double smoke detection system; a traditional one with spot type detectors in spaces of normal ceiling height and beam detectors lor bigger halls and a high sensitivity system based on continuous air sampling. The theater’s main hall and the stage were provided with both beam (on multiple levels) and spot type smoke detectors (one in each box). The high sensitivity system utilizes small tubes to carry air samples from the protected space using an air pump. The sampled air is analyzed in the device and is sensitive to very small changes in air composition. This system's sensitivity is reported to be 1000 – 2000 times higher than that of traditional smoke detectors. Consequently the signal from this detector is considered only as a pre-alarm notification for safety people, and does not activate automatic extinguishing systems.

Fire suppression systems

Two different extinguishing agents were utilized: water and gas (PF23). The gaseous agent systems are used in two spaces: the space underneath the parterre floor and the plafond zone. This kind of system was considered suitable for these unoccupied spaces, although the extinguishing gas has been tested and found non-toxic. Moreover this kind of extinguishing system is considered to be effective against possible arson fires started with liquid fuels.

In the first design version automatic fire sprinkler systems were provided for the stage, the boxes. and the attic. On the stage, sprinklers were positioned on two different levels, under the surrounding stage-shifter balcony and under roof structures. The sprinkler system also protected the presidium curtain and each level underneath the stage.

Later, a specific prescriptive regulation required extension of sprinklers to other spaces surrounding the parterre and boxes area (the main hall) to lower temperature during fire even though all these areas are constructed of noncombustible materials (plastered walls and ceilings, stone floors, etc.)

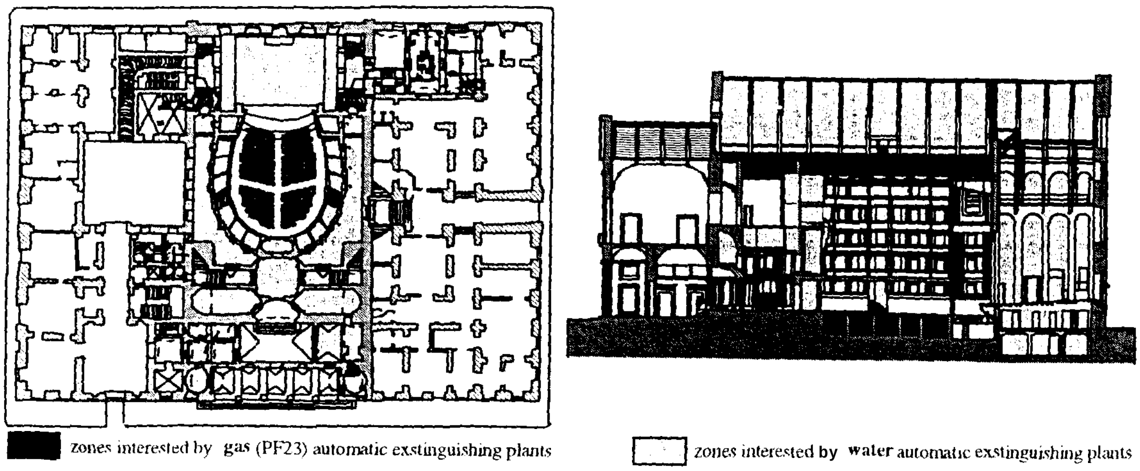

Figure 7 – Zones interested by **automatic water** and gas **extinguishing plants**

Special sprinklers would be used near the roof structures (stage and attic) that eject 40% of the flow towards the top (against wooden structures to wet them) and the remaining 60% towards the bottom. This requirement is intended to assure a longer ignition time in case of fire exposing these wooden structures without the provision of noticeable protection that might detract from their historical look. Treatments such as intumescent paints or varnishes are widely known to be marginally effective and to degrade over time. The same wooden structures were evaluated and shown to provide the required fire resistance time.

All water fire-extinguishing systems were fed by two pumping systems (one supplying the other in case of failure plus a backup power generator), two cisterns (one as reserve to the other) each one of roughly 200 cubic meters in capacity. The existing cisterns were part of the 19th century municipal water system that occupied the theater site prior to its construction. **A** number of such cisterns were found in the basement of the theater in excellent condition.

Computer control equipment

All theater system would be managed through a supervising electronic system provided with three control stations, one located at the main artist entrance, one at the town hall control place staffed 24 hours a day, 7 days a week by city patrol, and the third on the stage, with the possibility of future additions. such as in the theater's administrative office.

Through these control stations it is possible to observe all parts of the theater by means of a closed circuit TV system, receive alert signals by the intruder alarm system in rooms and on emergency doors, and to receive alarms from the smoke detector systems (high sensitivity and normal ones). The system provides on-screen information from the selected zone, control of the air conditioning and forced ventilation systems, control of the lights and emergency light operation, and control of the fire extinguishing system performance. This supervising system plays a significant role in the overall security level through continuous control and prevention.

Fire resistance of structures

By subdividing the theater into different compartments it was possible to reduce specific fire loads. This did not provide an advantage in meeting the structural fire resistance of 90 minutes required by a specific and somewhat controversial provision in the Codes. Two different types of structure had to be evaluated; existing wooden structures and the new steel ones related to the egress stairs.

Wooden structures

There were two types of wooden structures that needed to be considered – slabs (the floors of boxes and attic) and structural frame (trusses, pillars and beams). The slabs, in addition to lie resistance, had to be strengthened to coinply with a code specified load of 400 kg/m^2. The solution adopted for the slabs was a combination of wood and concrete. In the original construction these floors consisted of a layer of mortar and slag poured over the wood slab and covered by tiles. An analysis showed that a layer of reinforced concrete of 6 and 8 cm for the boxes and attic floors respectively would meet the performance requirements for fire resistance and load capacity. Steel pins inserted in the wood and locked with epoxy resin tied the concrete and wood layers together.

All wood structural frame elements are required to resist 90-minute fire exposure and were verified as meeting this requirement. Considering a fixed rate of reduction in cross section during fire exposure, the remaining cross section was sufficient to carry the required loads. But, particularly when dealing with a truss exposed to fire, failure of any node will result in structural failure of the truss. Thus, all nodes (trusses, pillars and beams) were mechanically secured by steel rods inserted in holes and scaled with epoxy resin covered by wood plugs to reduce heat transfer to the rods.

To achieve the required load capacity for the truss tie-beams which act as the main load bearing element for the attic floor, a typical 19th century solution common in building manuals of that period was chosen. The tie-beams were reinforced by means of a pre-stressed cable anchored to the ends and pushing up on the beam through a central rafter. Dywidag cables. high performance steel cables usually used for pre-stressed concrete. were employed to obtain the required force. While this arrangement is not original to this building it is appropriate to the period and as such presents a way to meet modern structural load requirements while preserving the building's character.

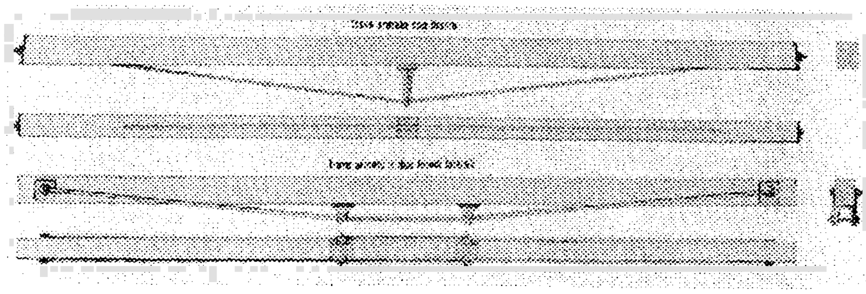

Figure 8 – The reinforced wooden **beam** - 19th century building manual
(Cattaneo L., *L'arte muratoria*, Vallardi, Milano, 1889)

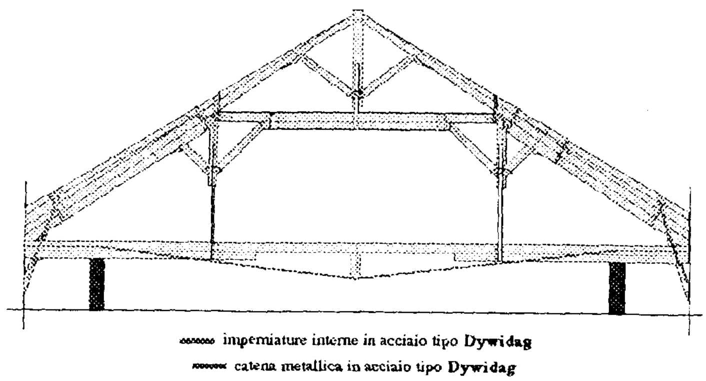

Figure 9 – Roof trusses: - tie-beams reinforced with pre-stressed Dywidag cables
- nodes fastened through steel rods.

Steel structures

The three new stairs were designed with a steel frame composed of square tubular bars. Local stone slabs on steel plates were specified **for** the steps. The idea was *to* use new materials and techniques that could later be removed if desired. The stairs were enclosed in 2-Hr fire rated construction. It was then required that the stair elements themselves had to have a 90 minute fire resistance. An analysis was performed to assess the performance of the *stair* when exposed to a peak temperature of 400° C, but in the end it was necessary to fire protect the structural steel with insulating plaster on a metal mesh. Finally, a gypsum ceiling was specified at the openings to avoid the industrial look of the insulating plaster.

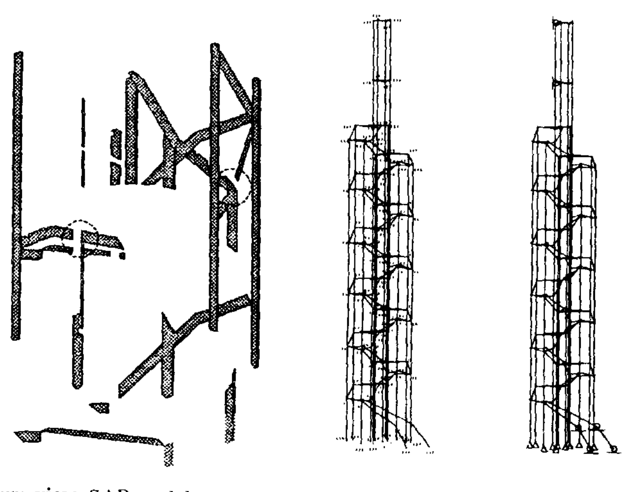

Figure 10 - Twin new stairs: plan configuration, structure **view**, SAP model utilized to assess performance under heating

Control of smoke spread through mechanical ventilation

A detailed analysis on smoke production and spread in case of fire was carried out to evaluate the benefits of smoke control in maintaining better conditions for both the audience and the fire brigade. This was done using the CFAST model developed in the U.S.[12 13]

Simulations were performed for two rooms - the parterre and boxes, and the new hall in the attic. The simulations considered three situations; no ventilation, smoke exhaust only, and smoke exhaust with make-up air of 30% to 60% of the volume exhausted.

To define the heat release rate the total amount of combustible material present was considered, and a constrained fire curve was defined that grows to a peak at 30 min., burns steadily for a further 60 min., and decays to extinction over 45 min. for a total fire duration of 135 min. The times took into consideration that structural collapse would not occur for at least 90 min. as previously determined.

The simulations were performed assuming that in the first 5-10 minutes the patrons will have escaped from the theater. Since these rooms are equipped with self-closing doors, the fire rooms remain closed (except where cracks around the doors were assumed). Beginning 20 minutes after the fire start the fire brigade were assumed to open some doors to attack the fire.

The results of the simulations reported elsewhere" showed that the 'no ventilation' case produced the greatest door flames (after 20 min.) and smoke opacity, temperatures and energy released comparable with those in the 'ventilation' case, initial increase of pressure, the lowest oxygen values, and gas concentrations comparable with those in the 'exhaust only' case.

The 'exhaust only' scenarios showed highest temperatures, fires and gas concentrations, lowest vent fires and pressures, intermediate oxygen levels, and smoke opacity comparable with that in the 'ventilation' case.

The 'ventilation' scenarios showed lowest temperatures, lower vent fires (comparable to those in the 'exhaust only' case), almost stable room pressures, highest oxygen levels, and lowest gas concentrations and smoke opacity.

Simulation results demonstrated much better interior conditions when the smoke control system included smoke exhaust along with make-up air at a rate of 30% to 60 % (according to different room conditions) of volume exhausted.

Conclusions

During all the design phases perforinance evaluations were crucial for defining solutions to be adopted. This was done by means of available methods, analyzing relevant phenomena and considering occupant egress.

This was the case for steel structures whose configuration and restraints were modified according to results obtained for a fire exposure resulting in a 400°C thermal gradient. With defined restraints and configuration the stairs keep their structural and functional efficiency in case of fire, for at least 90 minutes. This was not true for the first draft solution that caused unacceptable deformations and even structural collapse. Interestingly, this solution met the existing prescriptive code that deals only with the details of the protective materials. It can be shown that, even with protection according to the Codes, temperatures can be reached that can lead **to** serious problems with steel elements. There should be more emphasis on the development and use of calculation methods for the performance evaluation of steel under fire conditions, considering loads, design configuration, and restraint conditions.

Other considerations are related to fire certified materials. Protective and separating elements, such as insulating plasters and ceilings, are certified according to specific tests. Consequently they are suitable for use only when used with the same structural elements used during the tests. For example, if the temperature immediately on top of a protecting membrane reaches 200°C only after 120 minutes, this ceiling could be used to protect for the same period, a wooden structure that would reasonably start to burn only after this period. But if the ceiling was tested in conjunction with a steel structure, according to Italian procedures this does not determine its acceptability to protect wooden structures. This is also true for elements tested using wooden structures and not accepted to protect steel.

Applying the Codes literally, only ceilings certified as fire resistant independently from the type of protected structure can be accepted for general use. Among these there are a few, called “membrane ceilings”, whose performance meets the definition of a fire separating element (i.e., Eire resistance. no smoke penetration, unexposed side temperature lower than 150°C) and others, commercialized too as fire resistant independently from structure type, for which tests result **in** an unexposed side temperature of roughly 350°C. For these, certified according to a specific rule regarding non-load bearing elements. their acceptability depends on regulatory discretion or willingness *to* accept a technical evaluation.

Another interesting area identified in the present analysis regarded ventilation during a lire. The local Fire Brigade preferred a solution either without any exhaust system (based on lower fire growth or even smothering for lack of oxygen) or with only smoke exhaust. Based on the simulation results and considering the uncertainties of the modeling techniques employed, a compromise was offered where all fans were provided with control systems to adjust flows. Through either control from the supervising station or manual adjustments made at equipment controls made directly accessible from outside, exhaust and inlet flows can be varied as needed. **To** assure proper f’unctioning **of** exhaust fans during fire, water cooled fans were chosen that were tested to resist a temperature of 800°C.

All fire safety solutions as a system have been verified against a selected set of possible fire scenarios, including:
- fire on the stage;
- fire in the parterre:
- fire underneath the parterre;
- fire in the boxes;
- fire in the gallery;
- fire in the plafond zone;
- fire in the attic:

to assess the performance of the systems in mitigating the effects of fire.

In spite of the long approval process (about three years), the design achieved the result to respect and preserve historical wood structures and assure safety without detracting from the historical. construction and performance (i.e. acoustics among others) aspects of the theater.

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